

# SEISMIC DAMAGE FIELD OBSERVATION AND VULNERABILITY ANALYSIS OF MULTILAYER REINFORCED CONCRETE FRAME STRUCTURE

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## ABSTRACT

To research the seismic damage characteristics, mechanism and vulnerability of multi-storey reinforced concrete (RC) frame structures, statistics and analysis, were made on 930 RC frame structures in Dujiangyan during Wenchuan earthquake, China. Firstly, seismic damage of RC frame structure in Dujiangyan is investigated comprehensively. According to the investigation results, easily damaged locations of this kind of structural system are: infilled wall, frame column, beam-column, joints and stairs. However, a large number of RC frame structures are basically intact or slightly damaged. By using the method of numerical statistical analysis, the non-linear relationship model and the fitting curve of seismic damage investigation samples under multiple seismic damage grades are given. Considering the number of stories, multiple ages and seismic fortification influencing factors, the empirical seismic damage situation of structures under each factor is analyzed, and the non-linear regression curve is developed. The empirical seismic vulnerability matrix and continuous regression function model and curve of RC frame structure in multi-intensity region are established. A calculation model of mean seismic damage index (MSDI) is proposed, and the vulnerability matrix and regression curve based on this parameter are given in combination with the empirical seismic damage investigation data. The above research results can provide a basic reference for vulnerability analysis and intensity scale revision of RC structures.

## KEYWORDS

RC frame structure, Seismic damage field observation, Vulnerability analysis, Mean damage seismic index (MDSI), Seismic intensity

## INTRODUCTION

On May 12, 2008, at 14:28:4, Ms8.0 earthquake occurred in Wenchuan County, Sichuan Province, China. The instrument epicentre was located in Baihua Town, Wenchuan County, Aba Prefecture. The seismographs fault was located in the Longmenshan fault. The macro epicentre was located in Yingxiu Town, with a focal depth of 14km. The absolute disaster area reached 100,000 square kilometers. Earthquakes were felt in Southern China, Japan, Thailand and the Philippines [1]. Tsinghua University, etc. [1], has carried on the investigation of earthquake damage to RC frame structure, analyzed the damage characteristics of non-structural components such as enclosure structure and infilled wall. The causes of serious damage caused by poor construction quality and complicated structure layout are analyzed, and the seismic measures to improve the structure are put forward. Li Hongnan et al. [2], carried out on-site seismic damage observation on

engineering geology seismic damage, structural earthquake damage and lifeline project seismic damage. Three main damage characteristics of RC frame structure were given. Sun Baitao et al. [3], analyzed the damage characteristics and causes of multiple types of structures in Wenchuan earthquake, field investigated 5000 structural damage samples, and gave the failure characteristics of RC structures mainly in the maintenance structure, the junction of filling walls and beams and columns. Li et al. [4], through investigating and analyzing multiple typical seismic damaged structures in Wenchuan earthquake, the failure characteristics and causes of typical structures are given. Li et al. [5], Combined with 2178 bottom frame seismic wall structures in Dujiangyan City, conducted seismic damage investigation and analysis, and gave typical failure characteristics of this type of structure.

Manfredi. et al. [6], damage characteristics of RC frame structures in Emilia earthquake in Italy in 2012 are analyzed, and the intensity evaluation and vulnerability analysis of RC frame structures are carried out by using EMS-98 intensity scale. Westenenk.et al. [7], the damage analysis of frame shear wall structure in the 2010 Concepción earthquake in Chi Chi was carried out, and the failure proportions of the structure under N-S and E-W ground motions were given. Lin. et al. [8], the site investigation of the structural damage in Lushan earthquake in 2014 was carried out. The damage investigation pictures of column foot, joint, short column and masonry wall of RC frame structure were given. The acceleration time history curve was given based on the actual ground motion parameters. Maeda.et al. [9], combined with the seismic damage survey data from north-eastern Japan in 2011, carried out in-depth research. Considering the instrumental intensity theory, the acceleration time history curve and the acceleration response spectrum curve of 5% damping are given by using the ground motion parameters measured by different stations, and the vulnerability relationship between the seismic damage parameters and the seismic damage grade is established. Eleftheriadou.et al [10], collected the data of structural seismic damage investigation in southern Europe, established the vulnerability matrix based on 178578 buildings, calculated and gave the relative and cumulative frequency of each structural type and damage grade according to the damage ratio, obtained the vulnerability probability matrix (DPM) of RC frame structure, masonry structure and other typical structures.

In the field investigation, it is not comprehensive to select only some discrete survey points for structural seismic damage analysis and vulnerability study. In order to comprehend more accurately and comprehensively the damage characteristics of RC structures in a multi-intensity region, a vulnerability matrix based on empirical seismic damage is established and a typical region is selected. It is necessary to conduct comprehensive seismic damage investigation.

## FIELD OBSERVATION OF RC FRAME STRUCTURE

According to the analysis of the results of seismic damage investigation of RC frame structure in Dujiangyan city, this kind of structure is extensively used because of its flexible layout, easy to take large bays, strong practicability and mature construction technology. Therefore, the author and the relevant seismic damage investigators carried out a detailed investigation of the above vulnerable locations.

### Failure of filled wall

The failure of infilled wall is the most prominent in the investigation of seismic damage of RC frame structure. In the lower intensity zone, the horizontal earthquake action destroys the connection of frame column, beam and infilled wall, produces horizontal and vertical cracks around the extended infilled wall, as shown in Figure1.

In higher intensity zone, X-shaped cross-inclined cracks or unidirectional inclined cracks appear in the filling wall due to the reciprocating effect of ground motions. This phenomenon is more obvious at the opening of the tunnel, as shown in Figure 2. When the seismic parameters reach the peak value, the infilled walls absorb a lot of energy, and even collapse locally or wholly.

As shown in Figure 3, the main reason is the lack of effective tie with columns and beams. Plane instability occurs first under seismic action, which cannot well resist seismic action together with the main bearing members.



Fig. 1 – Cracks around filling wall

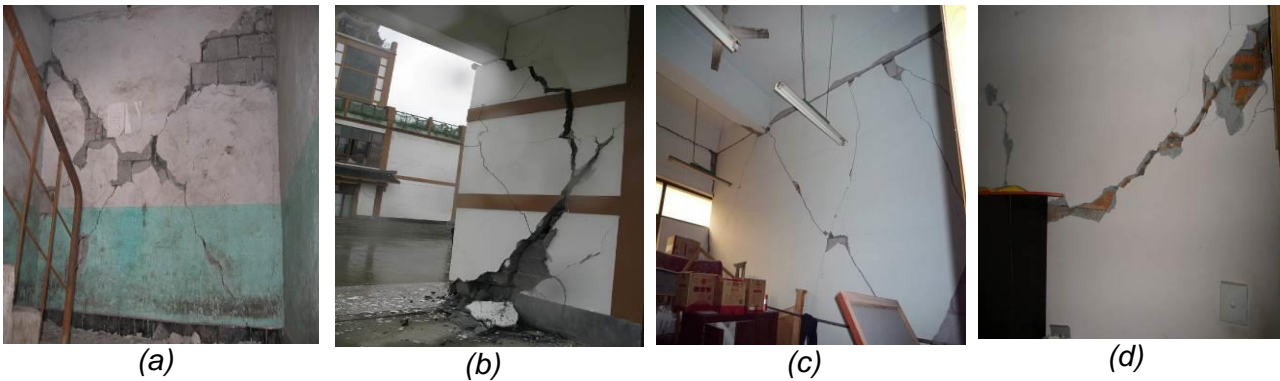


Fig. 2 – Filling wall cracks: (a) (b) (c) filling wall cross-oblique cracks; (d) opening unidirectional cracks



(a) Partial collapse of bottom filling wall

(b) Integral collapse of second-story filling wall

Fig. 3 – Filling wall collapse

However, from the analysis of the effect of the infilled wall, it has become the first seismic defence line of the whole RC frame structure to a certain extent, absorbed part of the vibration energy and played the role of energy dissipation and shock reduction. Therefore, the damage of the main structure has been delayed, especially in the higher intensity zone, which has played a role of protection for the principal structure in a certain sense. In seismic design, full consideration should be given to the anti-seismic effect of infilled walls to enable them to more accurately estimate the anti-seismic capacity of RC frame structures. The stiffness ratio between layers should be reasonably controlled to prevent damage caused by too weak bottom.

## Failure of frame columns, beams and joints

Depending on the results of seismic damage investigation of RC frame structure in Dujiangyan city, the damage characteristics of beams, columns and joints are basically the same as those of Muisne in 2016 and Emilia in 2012. Damage of frame columns is more serious than that of beams. Because of the complex force on the top of the column, under the coupling action of shear force, bending moment and axial force, brittle failure of concrete at the end, longitudinal buckling of reinforcing bars, failure of stirrups, inclined cracks and yielding of longitudinal bars often occur. Due to improper setting of stirrups on the top of the column, most of them are 90 degree bending hooks [10], incongruity effectively cooperate with the longitudinal bars to resist earthquake, and the stirrups of the column are insufficiently allocated or anchored, resulting in damage. As shown in Figure 4. The phenomenon of "strong beam and weak column" appears. Considering the effect of floor space and distributed reinforcement, and the excessive reinforcement of the beam, it contributes to the beam to a certain extent, resulting in lighter damage of the beam than that of the column. However, also a few cases of negative bending moment near the end of the beam, which leads to shear failure at the end of the beam, as shown in Figure 5. Under the influence of reciprocating seismic excitation, the beam-column joints are in the state of shear-compression composite stress, the concrete at the top of the column is peeled off, the steel bar is bent and exposed, and the crack damage occurs at the end of the beam, as shown in Figure 6. The low ratio of stirrups at joints leads to brittle failure. The poor quality of concrete pouring constitutes one of the factors leading to joint failure due to the dense arrangement of reinforcement at joints. The mechanism of beam hinges and "strong columns and weak beams" should be studied in depth to ensure that the structure has sufficient shear resistance and ductility, to control the axial compression ratio of frame columns, to consider appropriate enlargement of the design cross-section size of the bottom frame columns, to ensure their strength, and to ensure that the stirrup spacing at the top of the columns is small enough to ensure that the bottom has sufficient overall stiffness.



*Fig. 4 – Failure of frame beams and columns*



*Fig. 5 – Failure of frame beams end*



*Fig. 6 – Failure of joint*

## Staircase damage

The investigation found that staircase damage occurred in multi-intensity zones. Some outdoor staircase steps were broken into several sections, Steel bars were exposed and distorted and yielded, staircase platform beams and stirrups were broken. As shown in Figure 7, concrete was crumbed and the protective layer was severely peeled off, staircase panels were broken, as shown in Figure 8, a large number of staircase walls were cracked and damaged, as shown in Figure 9. The function of stairs is not considered in the calculation and analysis of seismic system of RC frame structures, but the investigation of empirical seismic damage shows that stairs increase the lateral stiffness of structures to a certain extent and contribute to seismic resistance. Stairs and staircases are subjected to considerable shear force and bending moment under reciprocating earthquake action. Serious damage often occurs at the end of staircase beams, slabs, and the middle part of the span. Steel bars leak out, buckle, and concrete to crumble. The

seismic design of stairs in RC frame structures should be considered reasonable to effectively improve the overall connection with the main frame.



*Fig. 7 – Fracture of stair platform beam*



*Fig. 8 – Stairboard midspan breakage and failure*



*Fig. 9 – Cracking of staircase wall*

### Structural collapse

In the investigation of seismic damage in high intensity regions, it was found that some RC frame structures without seismic design and poor construction quality had partial or overall collapse, which was more prominent in the Kashmir earthquake in Pakistan in 2005 and Simav earthquake in Turkey in 2011. The main reasons for the damage are that the structure layout is relatively complex. Some of these structures are generally located in township areas, built by the residents themselves, lack of formal design and construction supervision, random material selection and structural form, poor construction quality and high intensity regions, which to some extent aggravate the damage degree of the structure, such as Figure 10 shows. It is necessary to pay full attention to the seismic design of this kind of structure in township areas, and strictly follows the design specifications for construction in order to improve the quality of engineering structures.



*(a) Partial collapse*



*(b) Ensemble collapse of bottom layer*

*Fig. 10 – Collapse failure*

### Basically intact

In the investigation of RC frame structures, most of the buildings suffer less seismic damage, even almost intact. Most of these structures are multi-storey RC frame structures in earthquake regions. Even in the high intensity region of XI degree, there is still quite a number of such structures which have been designed aseismic. The damage grade is slight damage or basically intact. According to seismic fortification of VII degree in Dujiangyan city, this kind of structure shows great aseismic potential, as shown in Figure 11.



Fig. 11 – RC frame structure after seismic design basically intact

## FIELD OBSERVATION DATA ANALYSIS

The seismic damage investigation team conducted a total sampling survey of 8625 buildings in Dujiangyan city, and assessed the seismic damage grade of each building. The main structural types of the city: masonry structure (MS), bottom frame-seismic wall masonry structure (BFM), reinforced concrete frame structure (RC), single-storey concrete and brick workshop (SSB), and other types of buildings (OS). Figure 12 displays the number distribution of structural types in the city. According to the Chinese Seismic Intensity Scale (GB/T 17742-1999) and Appendix A1.2 of GB/T 1828.3-2000, the seismic damage grades of structures are classified into five criteria: destroyed (D5), severely damage (D4), moderately damage (D3), slightly damage (D2), and basically intact (D1). As shown in Table 1, seismic damage grades of structures are evaluated. In order to ensure that the records of seismic damage investigation more standard, the seismic damage grades are expressed by 51, 41, 42, 43, 31, 32, 33, 21 and 11, respectively. Due to the great difference of damage degree between D3 and D4 buildings, for better evaluation of the detailed seismic damage situation under the same seismic damage grade, the two grades are refined within their grades (31, 32, 33), (41, 42, 43), respectively. RC frame structure is widespread used in the developed and developing countries in the world, and the data are comprehensive. The number of seismic damage survey samples accounts for a certain proportion. In this paper, the seismic damage investigation and survey data of RC frame structures in multi-intensity regions are summarised and analysed.

### Data statistics and numerical analysis

Statistical analysis of seismic damage of 930 RC frame structures in Dujiangyan City is carried out, as shown in Figure 13. Figure 14 shows the damage of proportional distribution of the structure under multiple seismic damage grades. 72% of the structures are in D1 and D2. Most of these buildings can be designed and constructed in accordance with the applicable chapters of the Code for Seismic Design of Buildings (GB50011-2001, GBJ11-89), showing good seismic performance. RC frame structures of D3, D4 and D5 are mostly self-built buildings without seismic design or are located in high intensity regions, and the seismic action is relatively large. Through program editing and analysis, the Polynomial cubic and Gaussian quadratic fitting curve of the non-linear model can continuously approximate the discrete points of RC frame structure samples, the  $R^2$  value is above 0.98, therefore, we develop them as nonlinear vulnerability regression function models, two non-linear functional model, such as Formula (1) and (2), can be established to obtain the relationship between the seismic damage grade ( $R_D$ ) and the number of seismic damage

investigation samples ( $N_D$ ), among them,  $a, b, c, d, m_1, m_2$  are the regression parameters of the model. In which  $R_D$  refers only to the 9 seismic damage grades defined in this section. According to the empirical seismic damage survey sample data, using the above two non-linear models for regression, the empirical functional model and its fitting curve based on the grade of seismic damage and the number of seismic damage samples in the region are obtained, as shown in Formula (3), (4) and Figure 15. The investigation team found that the number of stories, construction age and seismic fortification factors of RC frame structure have a significant impact on the structural damage.

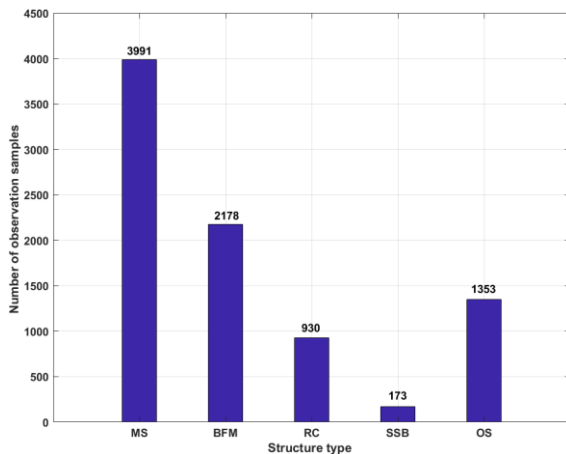


Fig. 12 – Quantity distribution of structural types in Dujiangyan city

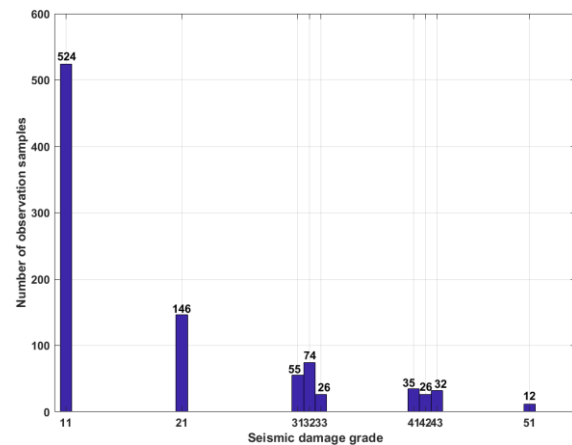


Fig. 13 – Statistical analysis of seismic damage of RC frame structure

Tab. 1: Quantification of provisions on seismic damage grades

Seismic damage grade	Quantitative description of provisions
D1	Bearing and non-bearing components intact, or individual non-bearing elements of slight damage, without repair can continue to use
D2	Individual bearing components have visible cracks and non-bearing components have obvious cracks. continue to use without repairs or minor repairs
D3	Most load-bearing components have slight cracks, some have obvious cracks, and individual non-load-bearing components are severely damaged, which can be used after general repair.
D4	Most of the load-bearing components are damaged seriously, and the non-load-bearing components collapse locally, so it is difficult to repair the buildings.
D5	Most of the load-bearing components were seriously damaged and the house structure was on the verge of fall or collapse.

$$N_D = aR_D^3 + bR_D^2 + cR_D + d \tag{1}$$

$$N_D = m_1 e^{-\frac{(R_D - n_1)^2}{p_1}} + m_2 e^{-\frac{(R_D - n_2)^2}{p_2}} \tag{2}$$

$$N_D = -0.0216R_D^3 + 2.55R_D^2 - 100R_D + 1340 \tag{3}$$

$$N_D = 1.166 \times 10^{17} e^{-\left(\frac{R_D + 492.5}{87.59}\right)^2} + 23.58 e^{-\left(\frac{R_D - 37.64}{15.81}\right)^2} \quad (4)$$

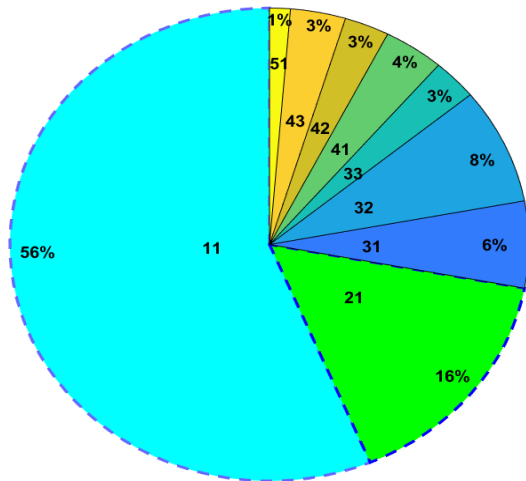


Fig. 14 – Proportion distribution of seismic damage grade of RC frame structure

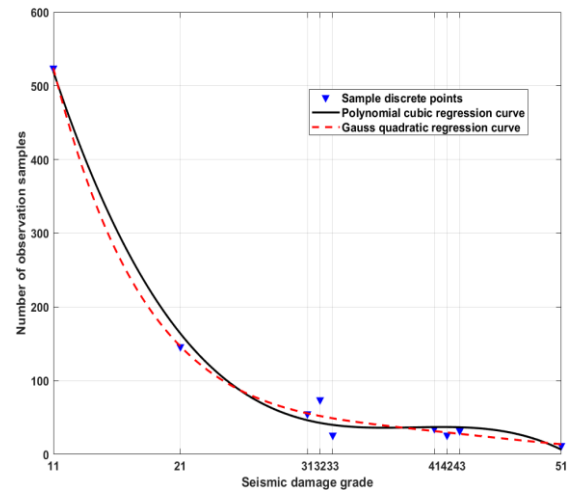


Fig. 15 – Nonlinear model curves of sample number and seismic damage grade

According to the visual inspection sample, the author carries on the statistical analysis separately. RC frame structure in this city, is mostly 6-storey and below buildings. Therefore, only 6-storey and below houses are analysed, which is representative to extent. A vulnerability matrix considering the floor number factor is established, as shown in Table 2. Figure 16 shows the damage ratio (DR) regression model curve (RMC) and cumulative transcendental probability curve (CTPC) of the structure considering story factor. The seismic damage of the first story RC frame structure is obviously lighter than that of other multi-story structures. On the overall trend, the damage grades of D3 and D4 increase with the increase of storeys. However, it is noteworthy that the seismic damage of a six-storey structure is weaker than that of five-storey, but more serious than that of other floor structures. Considering the sudden change of floor stiffness and the attenuation of ground motion, the mechanism of seismic damage is relatively complex, which should be paid attention to, and it is necessary to perform in-depth study.

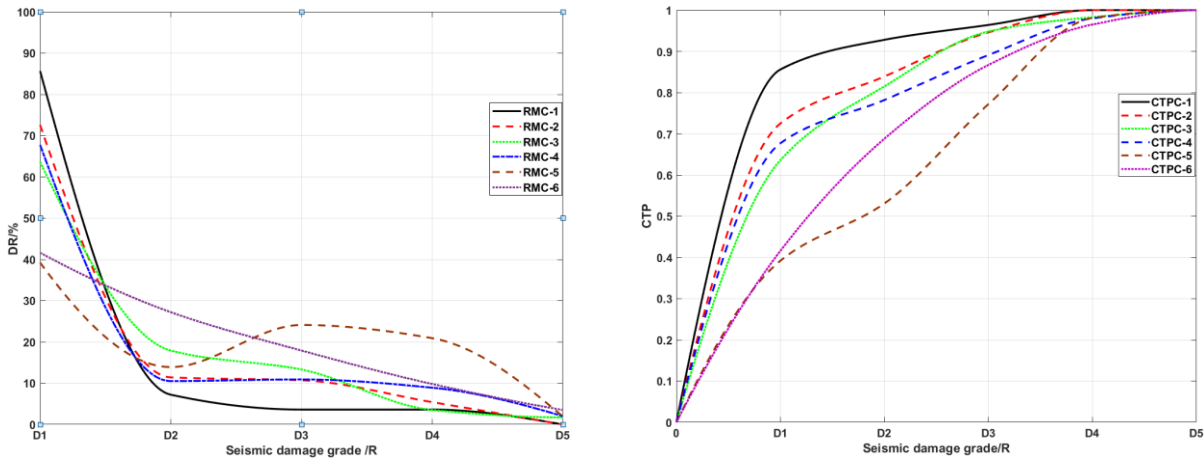
Tab. 2 - Empirical seismic vulnerability matrix considering storey number factor (%)

Structural floor number	D1	D2	D3	D4	D5
1	85.6	7.2	3.6	3.6	0
2	72.5	11.4	10.7	5.4	0
3	63.6	17.9	13.3	3.5	1.7
4	67.7	10.5	10.9	8.9	2
5	39.2	13.9	24.1	20.9	1.9
6	41.6	27.2	17.9	9.8	3.5

The influence factors of multiple ages of RC frame structure on the seismic damage of the structure remarkable discrepancy. 905 samples (25 unknown age buildings were excluded from 930) are divided into RC frame structures built before 1990, 1991-2000 and after 2001 according to the years, the empirical seismic vulnerability matrices based on the above ages are established,



respectively, as shown in Table 3. Figure 17 shows the damage ratio and cumulative transcendental probability regression model curves considering the age-dependent factors, respectively. The RC frame structure constructed before 1990 has the greatest damage rate. With the increase of the years, the damage rate of the structure decreases obviously.

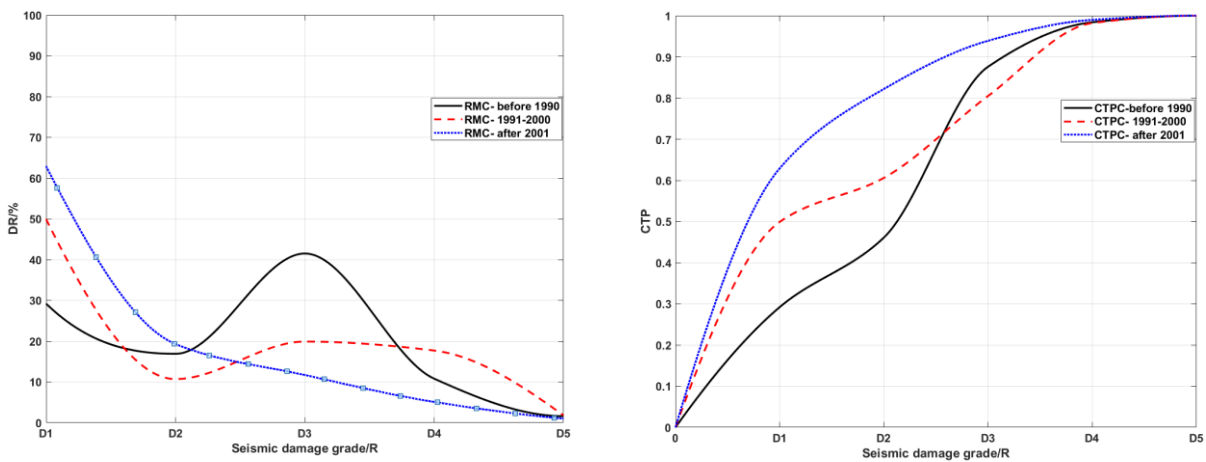


(a) Damage ratio regression model curve (b) Cumulative transcendental probability curve

Fig. 16 – Vulnerability curve considering floor factor

Tab. 3 - Empirical seismic vulnerability matrix considering chronological factor (%)

Age	D1	D2	D3	D4	D5
Before 1990	29.2	16.9	41.5	10.8	1.6
1999-2000	49.9	10.7	19.9	17.7	1.8
After 2001	62.9	19.3	11.7	5.1	1.0



(a) Damage ratio regression model curve (b) Cumulative transcendental probability curve

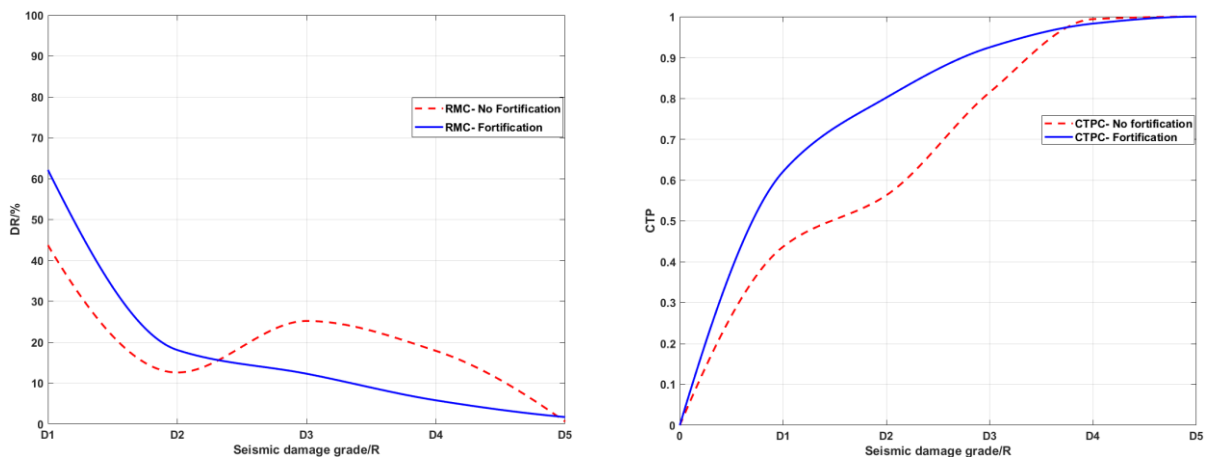
Fig. 17 – Vulnerability curve considering age factor

Whether the seismic fortification factor is taken into account in RC frame structures in the seismic damage investigation area has a relatively prominent impact on their damage. 904 buildings (26 buildings under reinforcement and construction are excluded from 930 samples) of the holistic field inspection sample are summarized, and the empirical regional seismic vulnerability

matrix based on this factor is established, as shown in Table 4. The numerical regression analysis is carried out and the curve of the non-linear regression model is given, as shown in Figure 18. The structure fortified according to the intensity of fortification in this zone is apparent superior to the structure constructed by township residents without considering seismic fortification. Most RC frame structures in the main urban area of Dujiangyan city can consider the impact of seismic factors on the structure. However, generous private buildings in towns and villages around the city, which do not consider the factors of seismic fortification, and bring about seriously damaged. The number of samples of RC frame structure D5 is scarce, so the regression curve is not remarkable for considering the difference of seismic fortification factors. To some extent, it also shows the seismic performance of RC frame structure in this huge earthquake.

Tab.4 - Empirical seismic vulnerability matrix considering seismic fortification factor (%)

Seismic fortification	D1	D2	D3	D4	D5
No fortification	43.7	12.6	25.2	17.9	0.6
fortification	62.1	18.1	12.3	5.8	1.7



(a) Damage ratio regression model curve (b) Cumulative transcendental probability curve

Fig. 18 – Vulnerability curve considering fortification factor

### Vulnerability analysis of empirical seismic damage

Vulnerability of building structures refers to the probability of various degrees of damage when structures are subjected to multiple earthquake actions. Vulnerability analysis is also called earthquake damage prediction in some literature. Vulnerability analysis can be split into empirical statistical method, theoretical calculation method and simple method based on seismic code according to the characteristics of the methods used [11]. In this paper, empirical analysis method is utilized to analyse the masonry structure of Dujiangyan city. Sampling method for seismic damage investigation is to take all samples from this city. Vulnerability analysis is mainly based on vulnerability curve and vulnerability matrix, while vulnerability matrix research is relatively less due to the larger sample size. This paper evaluates all RC frame structural samples of Dujiangyan city by using the quantitative standard of structural seismic damage clause in China Seismic Intensity Scale (GB/T17742-1999). Combining with probability theory model, structural vulnerability is analysed. The empirical seismic damage matrix of the structure type is established, as shown in

Table 5, SIR in the table represents the seismic intensity region. Considering that controversy in the initial delimitation of seismic intensity, the seismic damage in the region of VI degree is also considered in the investigation of seismic damage, and the probability curve of empirical seismic vulnerability is given, as shown in Figure 19. Figure 20 shows the structural damage under different seismic damage levels in multiple intensity regions.

Seismic intensity and damage grade are given as discrete integers in the application of structural damage assessment. It is difficult to achieve a more meticulous evaluation of seismic intensity and structural damage in a certain zone. Reference [12] establishes the attenuation model of seismic intensity and displacement, magnitude and regression curve to realize the continuous evaluation of seismic intensity. In reference [13], a vulnerability matrix based on the actual damage survey data of Athens earthquake in Greece in 1999 is established. The non-linear model curves between ground motion parameters (actual peak acceleration and reference acceleration ratio) and collapse ratio are given, and the continuous relationship between discrete ground motion parameters and collapse ratio is established. A continuous model of seismic damage grade and intensity should be considered, the seismic damage samples of 930 RC frame structures distributed discretely in multi-intensity areas in the city are analysed numerically. The Exponential quadratic fitting model is determined. However, the dispersion and variance of VIII and IX degree regions larger, and the fitting degree flat. Therefore, Polynomial quadratic fitting model is selected to model in these two intensity regions, as shown in formula (5-6). In the formula  $P_I$  represents the empirical damage rate of seismic damage under different damage grades in the I intensity region, and  $R_D$  represents the seismic damage grade.  $f, g, h, i, j, k, l, o, p$  represent regression parameter factors. Based on the regression analysis of the actual seismic damage survey data in the multi-intensity area, the parameter factors are determined, and the empirical vulnerability non-linear function model of the multi-intensity area in the city is established. As shown in Table 6 and Formula (7-12), the continuous distribution curve (CDC) is obtained, as shown in Figure 21. To a certain extent, the curve of the continuous model can realize the evaluation of the continuous seismic damage grade.

Tab.5 - Empirical seismic vulnerability matrix in multi-intensity regions (%)

SIR	D1	D2	D3	D4	D5
VI	89.2	9.7	1.1	0	0
VII	68.1	21.6	10.1	0.2	0
VIII	22.8	41	25.7	10.5	0
IX	9.8	15.1	21	42.6	11.5
X	6.2	8.1	12.4	21.8	51.5
XI	1.4	3.3	7.1	16.8	71.4

$$P_I = fe^{(gR_D)} + he^{(iR_D)} \tag{5}$$

$$P_I = jR_D^4 + kR_D^3 + lR_D^2 + oR_D + p \tag{6}$$

Tab.6 - Nonlinear continuous model of  $P_I$  and  $R_D$  in multi intensity zones

SIR	Continuous model of nonlinear function	
VI	$P_I = -0.01285e^{(0.2397R_D)} + 817.9e^{(-2.216R_D)}$	(7)
VII	$P_I = -0.03742e^{(0.7047R_D)} + 201.2e^{(-1.085R_D)}$	(8)
VIII	$P_I = -1.208R_D^4 + 17.68R_D^3 - 92.64R_D^2 + 190.5R_D - 91.5$	(9)
IX	$P_I = -3.479R_D^4 + 37.31R_D^3 - 136.6R_D^2 + 206R_D - 93.5$	(10)
X	$P_I = 4.603e^{(0.2573R_D)} + 0.03909e^{(1.358R_D)}$	(11)
XI	$P_I = 0.6716e^{(0.7849R_D)} + 1.816 \times 10^{-6} e^{(3.368R_D)}$	(12)

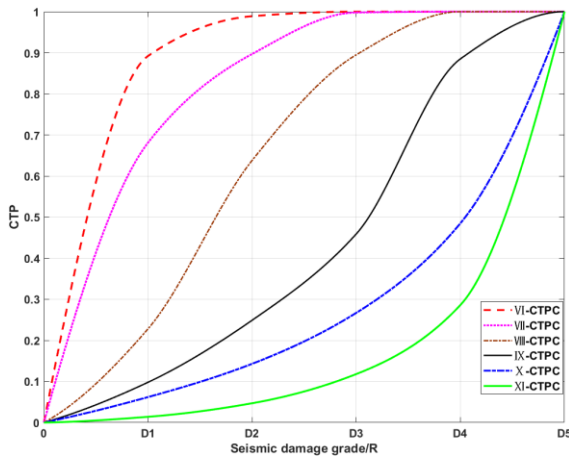


Fig. 19 – Vulnerability curve in multi-intensity regions

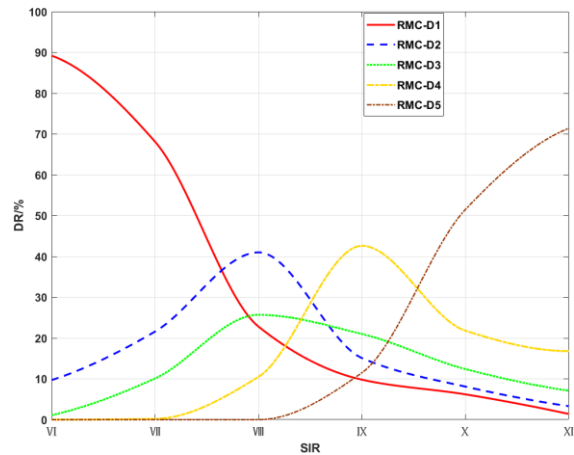


Fig. 20 – Seismic damage grades curve in multi-intensity regions

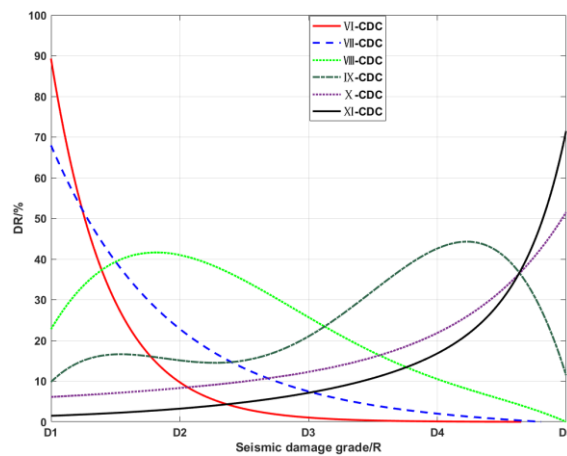


Fig. 21 – Continuous Model curve of Nonlinear Function n multi-intensity regions

### Seismic damage index analysis

To evaluate the overall damage of typical structures in a certain region more accurately, the concept of seismic damage index is introduced. Considering structural displacement, energy dissipation, structural modal, stiffness and site factors, 0-1 is used as a quantitative index to express the degree of structural damage. Among them, 0 represents no damage or failure, and 1 represents complete damage or failure [14]. In reference [15], the seismic damage index interval is split into [1,7], which represents the seismic damage of structures in multiple intensity regions. Reference [16] uses EMS-98 intensity scale to carry out structural vulnerability analysis, defines the seismic damage index as [0,5], establishes a functional model between vulnerability ratio, intensity and displacement, and applies it to the seismic damage index analysis in multiple intensity regions.

According to the empirical situation of seismic damage in Dujiangyan city, the seismic damage index ( $d_i$ ) used in this paper is a number between 0 and 1 to express the degree of seismic damage of structures from light to heavy [17]. The proportion of buildings damaged by earthquakes at all grades in empirical seismic damage investigation and the corresponding seismic damage index is calculated by a weighted average method. As shown in formula (13), the numerical value is called the mean seismic damage index (MSDI).

$$MSDI = \sum_{i=1}^5 d_i \cdot \eta_i \tag{13}$$

Tab.7 - Relationship between seismic damage grade and seismic damage index [14,17]

Damage grade	Median	$d_i$
D1	0.05	$0.00 \leq d_i < 0.10$
D2	0.20	$0.10 \leq d_i < 0.30$
D3	0.425	$0.30 \leq d_i < 0.55$
D4	0.70	$0.55 \leq d_i < 0.85$
D5	0.925	$0.85 \leq d_i \leq 1.00$

In the formula, the value of  $d_i$  is determined according to 5 seismic damage grades ( $i = 1,2,3,4,5$ ) and the Chinese seismic intensity scale. As shown in Table 7,  $\eta_i$  represents the ratio of the number of damages in the  $i$ th seismic damage grade to the total number of samples for a certain type of structure in a specific intensity region. According to the MSDI model and the vulnerability matrix established by the empirical seismic damage investigation, the matrix model of formula (13) is analysed and the MSDI matrix model is obtained, as shown in formula (14-16) where  $\eta_{ji}$  is the quantity damage ratio of RC frame structure in the state of damage grade  $i$ , when the seismic intensity (SI)=  $j$ .  $MSDI_j$  represents the  $d_i$  of a certain type of structure in  $i$  intensity region. By selecting the median and limit values of the  $d_i$  in Table 7 and combining with the empirical seismic damage matrix of RC frame structure, the vulnerability matrix of the structure based on the MSDI is given, as shown in Formula (17).

$$[MDI] = [d_i] \times [\eta_{ji}] \quad (14)$$

$$[MSDI] = \begin{bmatrix} d_1 \\ d_2 \\ \vdots \\ d_i \end{bmatrix} \times \begin{bmatrix} \eta_{61} & \eta_{62} & \dots & \dots & \eta_{6i} \\ \eta_{71} & \eta_{72} & \dots & \dots & \eta_{7i} \\ \eta_{81} & \eta_{82} & \dots & \dots & \eta_{8i} \\ \vdots & \vdots & \ddots & & \vdots \\ \eta_{j1} & \eta_{j2} & \dots & \dots & \eta_{ji} \end{bmatrix} \quad (15)$$

$$[MSDI] = \begin{bmatrix} MDI_6 \\ MDI_7 \\ MDI_8 \\ \vdots \\ MDI_j \end{bmatrix} \quad (16)$$

$$[MSDI] = \begin{bmatrix} 0.0687 \\ 0.1216 \\ 0.2761 \\ 0.5289 \\ 0.7010 \\ 0.8155 \end{bmatrix} \quad (17)$$

Figure 22 shows the regression curves of the MSDI in the multi-intensity region of the city. The empirical MSDI in the VI and IX regions is higher than the average values of D1 and D3 of  $d_i$  respectively, while the VII, VIII and IX regions are obviously lower than the slight damages and damages, and the MSDI in the X region is approximately equal to the average value of the  $d_i$ . The model analysis is basically consistent with the empirical observation damage investigation, which verifies the application value of the model to a certain extent.

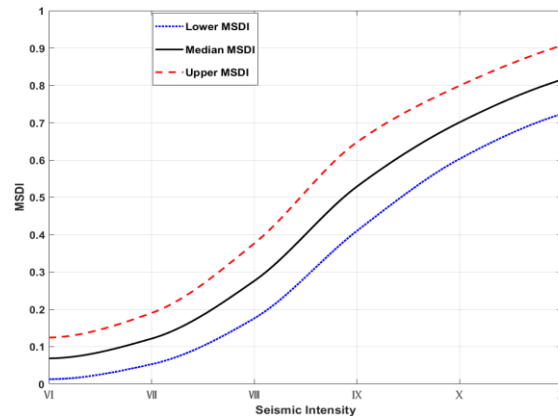


Fig. 22 – Regression curve of MSDI in multiple intensity regions

## CONCLUSION

To examine the seismic damage and vulnerability of multi-storey RC frame structures in multi-intensity regions, this paper investigates 930 such buildings in Dujiangyan city, Wenchuan earthquake China, a typical seismic zone with multi-intensity and ground-spanning. Structural vulnerability analysis is deeply studied and the following main conclusions are drawn:

- (1) 930 RC frame structures in Dujiangyan City were investigated and analysed for seismic damage. Typical damage locations were cracking or collapse of filling walls, beam-column and joints of frames, staircases, and local collapse or floor seating of individual structures in the high intensity region. However, a large number of buildings that have been fortified according to VII, showing good seismic performance.

(2) Statistical analysis of RC frame structure survey samples is carried out, and the overall seismic damage proportional distribution of the structure is given. The non-linear fitting model between the seismic damage grade and the number of damage samples is obtained, and the regression analysis is performed with the empirical seismic damage investigation data. Considering the influence of floor number, age and seismic fortification factors on structural damage, the vulnerability matrices of different factors are established, and the regression analysis curves are given. The vulnerability matrix based on the empirical seismic damage characteristics of Dujiangyan city is established. A theoretical method of continuous function non-linear model is advanced. Continuous non-linear relationship is established between diverse seismic intensity, multiple damage grade and failure ratio, and curve models are given, respectively.

(3) Applying the theory of SDI analysis, combining the empirical seismic damage vulnerability matrix of the multi-intensity regions of the city and the Chinese seismic intensity scale (GB/T 17742-1999), a matrix model based on the MSDI is proposed. The MSDI matrix of RC frame structure in the multi-intensity regions is obtained by using the vulnerability matrix of the zone for model analysis and calculation, and the regression curve of the MSDI is bestowed. Lines to verify the applicability of the matrix model.

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